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**LOW LOSS STRIATED  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$   
COATED CONDUCTOR WITH  
FILAMENTARY CURRENT  
SHARING**



**Paul N. Barnes  
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**DECEMBER 2004**

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# Low loss striated $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$ coated conductor with filamentary current sharing

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A simple investigation into the properties of weakly linked filaments in striated  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  (YBCO) coated conductors has been performed. Such weak-link connections may arise in two different contexts within the coated conductors, the one case being the occurrence of unintentional connections. However, it may be desirable to intentionally induce the weak-link connections in order to allow a current sharing between the filaments. This allows the localized degradation of a given filament to be circumvented at a small cost in terms of the added losses and magnetization. This problem has been treated mathematically with a comparison of the superconductor weak linking in contrast to the normal-metal-induced current sharing. The estimates for target values of filament coupling are deduced, and the results in terms of magnetization are then determined. The YBCO samples created, using the pulsed laser deposition, are described that have these properties. The samples consist of one control and one striated sample. The magnetization response of these samples is then considered in terms of the expressions developed. © 2004 American Institute of Physics. [DOI: 10.1063/1.1806554]

## I. INTRODUCTION

Ceramic high-temperature superconductor (HTS), used as a replacement for the copper wire in electric power applications, are typically formed in the shape of a thin tape that allows the HTS conductor to be bent around fairly small diameters. One method currently employed, especially with bismuth strontium calcium copper oxide (BSCCO), is for the tape to be fabricated as a multifilament, composite superconductor that includes individual superconducting filaments, which extend the length of the HTS conductor. In this case, the filaments are surrounded by a matrix-forming material, which is typically silver or silver alloy. Although the matrix-forming material conducts electricity, it is not superconducting, and together, the superconducting filaments and the matrix-forming material form the multifilament composite conductor.

An alternate method of HTS conductor fabrication uses a coated conductor technology, especially yttrium barium copper oxide (YBCO). The high degree of biaxial alignment required in the YBCO necessitates this architecture. In this case, the superconductor exists as a thin coating on a flexible substrate material. Sandwiched between the substrate material and the superconductor, there are typically additional thin buffer layers. The substrate is usually a metallic alloy, the most commonly used being Ni alloy. An additional layer of a silver or noble metal is coated on top of the superconductor to serve as a protective layer. Again, the form of the conductor is a flat flexible tape, although now, instead of individual filaments, the superconductor is a single thin layer within which the currents flow.

Advances in the YBCO coated conductors have resulted in dramatic improvements in the quality and length of the wire available—from  $10^5$  A/cm<sup>2</sup> at centimeter lengths a few years ago to lengths of several meters with  $10^6$  A/cm<sup>2</sup> performance.<sup>1–5</sup> These successes have been achieved by optimized deposition methods for the HTS layer; an improved buffer layer architecture, fundamental control of the biaxial alignment of either the initial ion-beam-assisted deposited and inclined substrate deposited buffer layer, or the underlying metallic substrate by a deformation texturing process.<sup>6–8</sup> Because of this success, the large effort given to the basic architecture of the YBCO coated conductor must begin to be also applied to issues such as ac loss, stability, and magnetic-flux pinning.<sup>9–12</sup> The minimization of ac losses is especially critical for the coated conductors, which, being highly aspected, have the potential for high losses in certain applications.

Even as presently configured, the HTS coated conductors are being considered for use in the rotor coil windings of superconducting generators and motors. With a sufficiently ac tolerant HTS conductor, the stator windings also might possibly be made of the HTS conductor leading to an all-cryogenic machine.<sup>13,14</sup> As such, long lengths of the conductor with a high transport current and lower ac losses are required to achieve these goals in rotating machinery as well as power transformers. The HTS coated conductor will experience a variety of losses in an environment with alternating applied magnetic fields. These losses include hysteretic, ferromagnetic, eddy-current, coupling-current, and transport-current losses as examples. Lowering these losses will decrease the refrigeration load allowing the HTS generators, motors, and transformers to be as compact and lightweight as possible.

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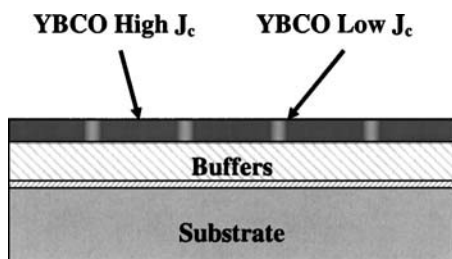


FIG. 1. Cross-sectional diagram of an YBCO thin film on a buffered substrate with a parallel patterning.

The hysteresis loss in the superconductor is proportional to the width of the filament perpendicular to the applied field. Thus, the largest losses are for the fields perpendicular to the wide face of the tape. A way to reduce these losses is to filamentize (stripe) the HTS layer.<sup>9,15,16</sup> These superconducting filaments must be “sufficiently” separated along the entire length of the HTS conductor. Fundamentally, this requirement amounts to a limitation on the amount of possible current flow per unit length between the filaments; practically, this means that the interfilamentary regions can be fully insulating, resistive, or even very weakly superconducting. A potential drawback of filamentation is that if a blockage occurs anywhere along the length of the filament, the filament becomes ineffectual for the current flow. If the interfilamentary connection is fully insulating, the net transport current through this filament is zero. Multiple “broken” filaments would then seriously reduce the current carrying capacity of the HTS conductor. This paper specifically addresses the issue of creating a low ac loss multifilamentary YBCO tape while still allowing for some level of current sharing. Subsequently, we describe a conductor where the current sharing is enabled by the weak superconducting linkages between the filaments. These weak links may either be in the form of a homogeneous, lower current-density ( $J_c$ ) region separating the filaments, or small superconducting bridges dispersed along a resistive barrier. Figure 1 depicts a cross section of such a sample.

## II. CURRENT SHARING

To make the HTS conductors useful in the aforementioned power applications, not only do the ac losses have to be reduced, but the stability, quench protection, and current sharing between the filaments must also be addressed.<sup>17–20</sup> Stability is necessary because this deals with the tendency of the conductor to remain in the superconducting state. Stability is typically achieved by the addition of a conductive layer, such as Cu or Ag, in direct contact with the HTS layer. Quench protection is also important to safeguard the conductor, and the device as well, from a quench-induced, irreversible damage. Quench protection is typically device dependent. Current sharing, the third item mentioned earlier, is particularly useful with thin HTS filaments. Small, localized instabilities or defect inclusions may occur within a filament, rendering the entire length of an individual filament useless. If this filament can current share with all the remaining filaments, then the filament is only ineffectual in the neighborhood of the defect or instability.

Most superconducting materials are contained within or are otherwise associated with metallic “carriers,” such that, in all practical cases, metallic regions separate the filaments of multifilamentary conductors. This is the case with the low-temperature superconductors and BSCCO multifilamentary composite tapes. The metallic matrix creates a useful situation in which the hysteretic losses are reduced by the filamentation, whereas the metallic connection between the filaments is sufficient to enable current sharing within the strand.<sup>21,22</sup> However, this leads to a certain amount of “coupling eddy-current loss.” This kind of eddy-current loss is proportional to the interfilamentary conductivity, and thus gets worse as current sharing improves. With a sufficient connectivity, the coupling eddy-current losses are sufficient to vitiate the effects of the filamentation, with respect to the overall ac loss reduction.

Particularly troubling for high-frequency applications is that the recoupling of the filament increases with frequency. As such, it is difficult to include any kind of normal metal conductivity-enabled current sharing in a multifilamentary strand intended for high-frequency (100–1000 Hz) applications. Indeed, this is true for any superconducting material, and is one of the factors that has generally precluded the consideration of a superconducting wire for high-frequency applications. Superconducting currents, on the other hand, are frequency-independent. Thus, it is possible to conceive of a low-level superconducting connection that will enable a frequency-independent current sharing, while still maintaining low ac losses. This should allow the construction of highly filamented YBCO conductors with a low loss, but with maximal transport properties.

HTS coated conductor tapes can be subdivided into thin filaments to decrease hysteresis losses in the alternating magnetic fields. The resulting multifilamentary structure is a tape with parallel thin strips of a high-temperature superconducting material, which, while filamented, could be cross connected in some manner. The metallic links, which serve this function, exist in multifilamentary BSCCO 2223 strands with a filamentary breakage, and the influence of such linkages on  $J_c$  has been detailed in Refs. 21 and 22. However, we wish to consider the tradeoff between the ac loss and current sharing for both the superconducting as well as the metallic links that occur either accidentally or intentionally. These links could be established as narrow bridges connecting the filaments at discreet locations, or as low critical  $J_c$  continuum connections along the length of the filament. It is also possible for the links to be established as a combination of these two schemes. These links can be induced at a level low enough to avoid an undue enhancement of loss (to an extent much above that of the base line filament-based hysteretic loss) but sufficient to allow some level of current sharing. This paper specifically deals with the creation of low  $J_c$  continuum connections along the length of the filament; the creation of discreet bridges for interconnectivity will be discussed in a later publication.

## III. EXPERIMENTAL DETAILS

The approach used in the present work was to divide the HTS tape into superconducting filaments separated by low  $J_c$

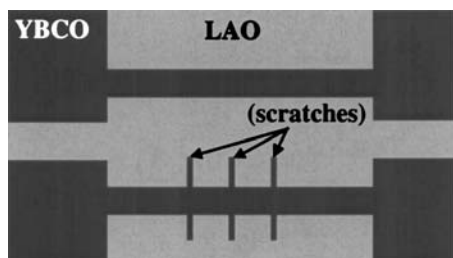


FIG. 2. Schematic planar view of the dual-bridged YBCO thin film on LAO with one bridge over the scratched substrate.

barriers. To accomplish this, the substrate was physically scribed to adversely affect the subsequent epitaxial growth of the YBCO. The YBCO ( $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ ) growth was accomplished by a pulsed laser deposition. A Lambda Physik laser, model LPX 305i, operating at 248 nm, the KrF wavelength, and pulsing at a 4-Hz rate performed the depositions. The substrates used were single-crystal  $\text{LaAlO}_3$  (LAO), which were ultrasonically cleaned for 2 min. A thin layer of a colloidal Ag paint was used to attach the samples to the heater. The background pressure of the chamber prior to the deposition was  $<10^{-6}$  Torr. The oxygen deposition pressure was 600 mTorr, kept constant by a downstream flow control, while an  $\text{O}_2$  gas (99.999% purity) flow was introduced during the growth. The deposition targets were rotated and rastered radially during the deposition for the uniform target wear. The laser fluence was approximately  $3 \text{ J/cm}^2$ . The substrate temperature was  $\sim 790^\circ\text{C}$  as determined by an optical pyrometer. Postoxygenation of the films were conducted *in situ* by lowering the temperature to  $500^\circ\text{C}$  and raising the oxygen pressure to 700 Torr. After 0.5 h, the heater was shut off.

Two sets of samples were prepared for the different investigations. For the first investigation, three parallel cuts were made on the LAO substrate using a razor blade in a strategic location on the sample for later patterning of the YBCO to create bridges. (Refer to Fig. 2.) The LAO sample was completely coated with YBCO by pulsed laser deposition. The YBCO film thickness was  $\sim 0.3 \mu\text{m}$ . After the YBCO deposition on this scribed substrate, two bridges were formed on the YBCO coated LAO; one overtop the scratches, and one on an unaffected area of the sample. The dual bridge structure of the YBCO was created by placing a precut mask made of alumina over the sample, and laser ablating the exposed YBCO film at an atmospheric pressure. The transport  $J_c$  was acquired by the four-point contact method using pogo pins for the current contacts and a  $1\text{-}\mu\text{V/cm}$  criterion. On these samples, the current and voltage contacts for the resistive measurement were patterned onto the films by a dc magnetron sputter deposition of Ag with  $\sim 3\text{-}\mu\text{m}$  thickness. The contact resistance of the Ag capped different films was reduced by annealing in pure  $\text{O}_2$ .

For the second investigation, two separate samples were created using LAO substrates,  $3.0 \text{ mm} \times 12 \text{ mm}$  in size. One LAO substrate was scribed with a diamond-tipped scribe. Six parallel striations were made  $0.4 \text{ mm}$  apart along the full length of the sample as determined with the system micrometer. As such, the outer two filaments were closer to

$0.5 \text{ mm}$  in width, accounting for the  $3.0\text{-mm}$  width of the sample. The scribing speed was  $5 \text{ mm/min}$  with a force of  $8 \text{ N}$ . The YBCO was deposited on this sample using the conditions given earlier. During a separate deposition, the other substrate was also deposited with the same conditions. Both the YBCO films deposited were  $\sim 0.3\text{-}\mu\text{m}$  thick.

Vibrating-sample magnetometry (VSM) measurements were made on the second set of samples to determine the hysteretic losses. The samples were mounted such that the field was applied perpendicular to the wide face of the sample with currents induced in the  $a$ - $b$  planes of the HTS films.  $M$ - $H$  loops were obtained in 10-min collection periods at several temperatures ranging from  $4.2$  to  $77 \text{ K}$ . Temperatures were determined by a Si diode placed near the sample. The superconducting onset transition temperature ( $T_c$ ) of the YBCO films were measured using an ac susceptibility technique. The amplitude of the magnetic sensing field varied from  $0.025$  to  $2.2 \text{ Oe}$ , at a frequency of approximately  $4 \text{ kHz}$ . The onset  $T_c$  measurements were accurate within  $\leq 0.1 \text{ K}$  at three calibration points; liquid He at  $4.2 \text{ K}$ , liquid  $\text{N}_2$  at  $77.2 \text{ K}$ , and room temperature.

#### IV. RESULTS

In the first investigation, the critical current of both bridges in the dual-bridged sample were measured by a four-contact transport measurement. The reference bridge, without the underlying scratches, carried a critical current ( $I_c$ ) of  $1.85 \text{ A}$ . The bridge with the perpendicular underlying scratches carried a  $I_c$  of  $0.28 \text{ A}$ . In the latter case, the transport current was measured such that the current must cross through the induced barriers. This clearly shows that the drop in the critical current is due to the striations as is expected from a poorer epitaxial alignment. This only implies that the superconducting currents are blocked above  $0.28 \text{ A}$  in at least one of the striations, not necessarily in all. Above this critical current, nonsuperconducting currents may flow, but the striations are resistive in nature.

This experiment was sufficient to demonstrate the basic effect of substrate scribing. It remained to be determined just what level of  $J_c$  reduction was needed and to further demonstrate it between the filaments of a YBCO sample with a more prototypical conductor geometry. These further efforts are described subsequently, where an alternate more-controlled scribing system is used. The diamond scribe is capable of a deeper scratch capable of more effectively disrupting the epitaxial template of the LAO substrate for a subsequent nonepitaxial YBCO growth. As such, further optimization of scribing the substrate can further reduce the weak link  $J_c$ , and demonstrate that such conditions are realizable in striped YBCO conductor geometries.

Having simply demonstrated the ability of the underlying substrate surface scratches to cause low  $J_c$  links between the filaments, the second investigation was conducted to measure the actual reduction in the hysteretic loss. Figure 3 displays the ac susceptibility data associated with the deposited YBCO film. The onset  $T_c$  is slightly greater than  $90 \text{ K}$  with a narrow spread of the loss data at varying magnetic fields indicating good films.<sup>23</sup> Figures 4–6 are the  $M$ - $H$  loops



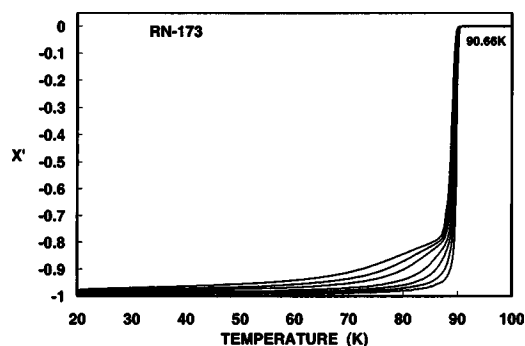


FIG. 3. Ac susceptibility data for the deposited YBCO film. The different curves result from the different applied fields listed in the legend—the field increases from right to left (from 0.025 to 2.2 Oe).

obtained at different temperatures. The lines are labeled for the nonstriated sample (control) and the striated sample (weak linked). The total hysteretic loss experienced in the sample is the area inside the curve; hence, the smaller the area, the lower the loss. The data clearly indicates that a reduction in the hysteretic loss occurs.

It has been previously demonstrated that the hysteretic loss is linearly proportional to the effective width of the YBCO filament in a sample when highly resistive barriers are used.<sup>9</sup> In this case, where the width of the filaments are one-seventh the width of the sample, the maximum loss reduction will be one-seventh. However, as evidenced from the given  $M$ - $H$  loops, slightly less loss reduction is observed. (Refer to Fig. 7.) The exact amount of the reduction is somewhat dependent on both the field and temperature. The field dependence is seen mostly near the origin, this may either be due to the presence in the control sample of “very” weak links at low fields (ignored for all practical applications) or a change in the demagnetization factor at very low fields. The variation with temperature is not very great with the ratio of the striped to the control sample magnetization ranging (in the field-saturation regime) from 3 to 4.

## V. DISCUSSION

The results, just presented, demonstrate the ability of the predepositional scribing to reduce  $J_c$ , and that low  $J_c$  linkages can potentially be used to filamentize the YBCO conductors. However, it is not *a priori* clear how low the effective  $J_c$  of the barrier must be, or with bridging, how small the bridges must be compared to the length of the resistive bar-

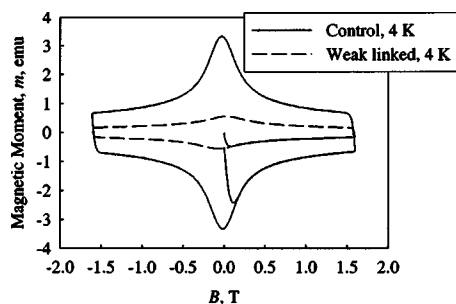


FIG. 4. Magnetization curves for the weakly linked sample and the control sample at a temperature of 4.2 K representing the reduction in a hysteretic loss.

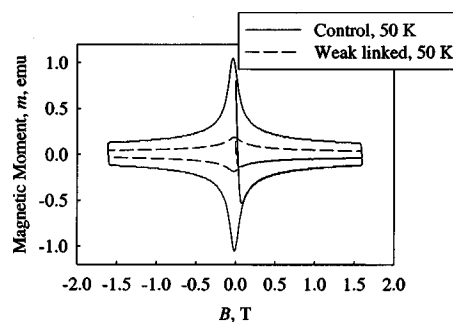


FIG. 5. Magnetization curves for the weakly linked sample and the control sample at a temperature of 50 K representing the reduction in a hysteretic loss.

rier. For an unfilamentized conductor, the hysteretic losses can dominate at low frequencies, whereas at high frequencies, the normal-metal eddy currents become important. Even when the hysteretic losses are reduced by striation, in a realistic conductor configuration, a coupling eddy-current effect will be generated, which strives to “recouple” the filaments necessitating the tape be twisted. Without the twist, large conducting loops exist, even if only due to the connections at the ends. Since striated conductors will require some effective twist, some connectivity is allowable.

## A. Superconducting link

To consider the usefulness of any current-sharing scheme used to circumvent the current limitations originating from the localized filamentary degradations, several assumptions need to be made. First, the degraded regions to be compensated for must not be too frequent and must not be concentrated in a localized area. Even if all of the filaments have degraded regions, we must assume that these regions will occur only occasionally and randomly. We can then describe the separation of any one from another by a characteristic length  $L_b$ . In addition, when the current is redirected around a given filament, we must require that the current is able to redistribute to all of the filaments in the cross section and not just to a nearest neighbor. The distance  $L_b$  must be greater than the distance required to transfer the current into the other strands,  $L_c$ . By allowing the current to share among all the strands, the  $I_c$  of the whole conductor will only be degraded by  $I_c/n$ , i.e.,  $I_c' = I_c (1 - 1/n)$  regardless of the number of defects and filaments affected.

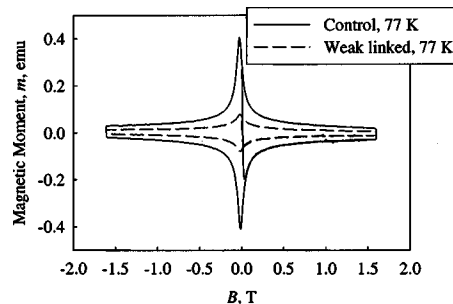


FIG. 6. Magnetization curves for the weakly linked sample and the control sample at a temperature of 77 K representing the reduction in a hysteretic loss.

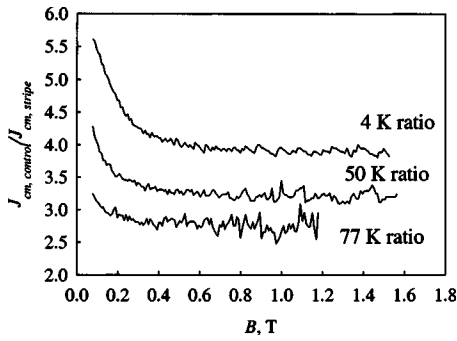


FIG. 7. Comparison of the relative hysteretic loss reduction of the weakly linked sample vs the controlled sample with respect to the applied field and temperature.

It is necessary to make sure that the linkages that allow current sharing do not substantially degrade the ac loss suppression. However, we must also require that the weak-link current is sufficient to permit the desired level of current sharing. We can define a relationship between the weak  $J_c$  perpendicular to the filaments,  $J_{cw}$ , and the recoupling length,  $L_c$ , as

$$J_{cw}L_c = J_{cf}d_f$$

or

$$J_{cw} = \frac{J_{cf}d_f}{L_c}, \quad (1)$$

where  $J_{cf}$  is the filamentary  $J_c$  along the strand, the filamentary width is  $d_f$ , and the length needed for the current transfer as specified before is  $L_c$ .<sup>24</sup> As previously stated, we must require that  $L_c$  be equal to or less than  $L_b$ . Equation (1) is essentially the requirement that the critical current of an individual filament is equal to the critical current of the weak-link connection over the required length,  $L_c$ .

We now must add a requirement limiting the loss of the sample. We do this by specifying a certain twist pitch,  $L_p$ . We can then require the product  $J_{cw}L_p$  to be some fraction or multiple of  $J_{cf}d_f$ . In theory,  $J_{cw}L_p$  could be made arbitrarily small, and it is worthwhile to note that this requirement is a separate one from Eq. (1). In particular, Eq. (1) puts a lower limit on  $J_{cw}$ , whereas this latter consideration puts an upper limit on  $J_{cw}$ . However, as a practical matter, we want to let  $L_p$  be as large as possible to avoid a strain-related degradation. Thus, we can take the simplified (degenerate) point of view that we require  $L_c < L_b$ , but put  $L_p = L_c$ . This then, at the same time, limits the additional loss to not more than the loss of an individual filament (additive, so that the total loss is now two times the loss of one filament per unit volume), and that the current flowing in the weak link is just equal to the current of an individual filament.

If  $L_p$  exceeds  $L_c$ , losses will increase up to  $L_p = nL_c$ , where a full magnetic filamentary recoupling will occur. As a specific example, let  $d_f$  be 100  $\mu\text{m}$  and  $L_c = L_p = 20$  cm. Then  $d_f/L_p = 5 \times 10^{-4}$ , such that  $J_{cw}$  is 2000 times smaller than  $J_{cf}$ . As per this example, it is possible to define a frequency-independent value of  $J_{cw}$  that may be useful in the current sharing.

## B. Metallic link

The previously described superconducting link-enabled current sharing must be compared to the standard method of using a normal metal to allow current sharing between the filaments. First, it must be determined what resistivity and cross section of normal metal are needed to allow for an acceptable current sharing. The transfer current will generate a voltage

$$V_t = I \cdot R = \frac{I_c \rho w}{n L_c t}. \quad (2)$$

Here,  $I_c/n$  is the current in an individual strand,  $w$  is the whole conductor width,  $t$  is the normal-metal thickness,  $\rho$  is the normal-metal resistivity, and  $L_c$  is again the transfer length. It can be considered that for the current sharing to be deemed effective, the electric field along the strand must be below the critical current criterion. In this case, the voltage (per unit length) in Eq. (2) is associated with the electric-field criterion for the HTS transition, which implies that  $(V_t/L_b) = 1 \mu\text{V/cm}$ . Using Eq. (2) leads to

$$10^{-4} \text{ V/m} \geq \frac{I_c w}{L_c L_b n t \rho}. \quad (3)$$

This puts an upper limit on the allowable resistivity. This requirement is not difficult to meet; if the metallic link is Ag and  $L_b > 20$  cm, the required thickness of Ag will be  $< 9 \mu\text{m}$  for a 100 A, 0.4-cm-wide tape with 100- $\mu\text{m}$  filaments. A composite with a Ag/Cu bilayer would give a very similar result. However, the real difficulty comes from the loss that this conductivity engenders.

In general, the per cycle eddy-current loss generated by this resistivity is given by

$$Q_e = \frac{L_p^2 B_m^2 f}{2\rho}, \quad (4)$$

which may have a demagnetization factor associated with it (which is ignored in this case). Here,  $f$  is the frequency and  $B_m$  is the maximum field sweep amplitude.  $L_p$  is the twist pitch, which again is set to be equal to  $L_c$ . Note that  $M_e = \mu_0 Q_e / (4B_m)$ . We can require, as discussed earlier, that the loss or magnetization of the current sharing enabled elements be equal to that of the filamentary loss. This will result in a doubling of the loss over the noncurrent sharing state, but such loss will still be much less than the unfilamented conductor. Using this, then

$$\frac{\mu_0 J_{cf} d_f}{4} = M_f = M_e = \frac{\mu_0 L_p^2 B_m^2 f}{8\rho}. \quad (5)$$

Solving Eq. (3) for  $\rho$  and inserting in Eq. (5), we find an upper bound on frequency, below which the loss is less than the maximal amount allowed. This limit is given by

$$f < \frac{2 \times 10^{-4} L_b}{B_m w L_c}, \quad (6)$$

where  $B_m$  is in tesla and  $w$  is in meter. Assuming a 1.5-T field with  $w = 0.004$  m,  $f = 60$  Hz, and  $L_c = 0.20$  m, the characteristic distance between the defects,  $L_b$ , must be not less

than 360 m for the normal-metal current-sharing scheme to work. This is a relatively low density of defects. Of course, if the defect did not cause a total blockage of the filament, the defect separation length could be reduced.

### C. Linkage comparison

It may be worthwhile to directly compare these two possible current-sharing schemes. The ratio of the eddy-current current-sharing mechanism to the filamentarized hysteretic loss gives

$$\frac{M_e}{M_f} = \frac{B_m f w}{2 \times 10^{-4}} \left( \frac{L_p}{L_b} \right). \quad (7)$$

On the other hand,

$$\frac{M_{wc}}{M_f} = \frac{J_{cw} L_c}{J_{cf} d_f}. \quad (8)$$

But if, parallel to letting the voltage in the eddy-current case develop along  $L_c$  only, we set  $J_{cw} = J_{cf}(d_f/L_b)$ , we get that  $M_{wc}/M_f = L_c/L_b$  with of course the caveat both here and in Eq. (1) that  $L_c$  must always be less or equal to  $L_b$ . In that case, we can take the ratio of the magnetizations (losses) of the two cases such that

$$\frac{M_{wc}}{M_e} = \frac{2 \times 10^{-4}}{B_m f w}. \quad (9)$$

Here,  $B_m$  is in tesla,  $f$  is in hertz, and  $w$  is in meter. Thus, if  $B_m = 1$  T and  $w = 1$  cm, then  $f$  must be subhertz in order for a better optimum to be possible with the eddy-current-enabled current sharing. Thus for dc applications (at any field) and for low-field applications, the eddy-current enabled current sharing will always be superior. However, for moderate and high-frequency applications, the superconducting link-enabled current sharing will have a better loss-sharing tradeoff.

### D. Analysis for experimental samples

In general, the magnetization for a coated conductor is given (for the face-on orientation) by  $\Delta M = w J_c / 2$ . This is for an infinitely long, unstriped sample of width  $w$ , where demagnetization is ignored for simplicity. For short segments, we can apply the standard expressions for finite length samples,<sup>25,26</sup>

$$\Delta M = \frac{w J_{c1}}{2} \left[ 1 - \frac{w}{3L} \frac{J_{c1}}{J_{c2}} \right] + \frac{w J_{c1}}{2N}, \quad (10a)$$

$$\Delta M = \frac{L J_{c2}}{2} \left[ 1 - \frac{L}{3w} \frac{J_{c2}}{J_{c1}} \right] + \frac{w J_{c1}}{2N}. \quad (10b)$$

Here,  $J_{c1}$  is the filamentary  $J_c$ ,  $J_{c2}$  is the weak  $J_c$ , and  $L$  is the sample length. For longer, twisted samples,  $L_p$  will fulfill a similar role to that of  $L$ .<sup>23</sup> Equation (10a) is applicable if  $J_{c1}/J_{c2} < L/w$ ; otherwise, Eq. (10b) is to be used for  $J_{c1}/J_{c2} > L/w$ . In the present case, for the samples used in Figs. 4–7,  $L = 12$  mm, and  $w = 3$  mm. Thus, for the unstriped control sample,  $\Delta M_{\text{control}} = (11/24)w J_{c1}$ . Assuming for the moment that  $J_{c2}$  is relatively weak (which can be verified to

give a self-consistent result), we apply Eq. (10b) and find that (inserting  $J_{cw}$  and  $J_{cf}$ , relevant to our present case)

$$\frac{\Delta M_{\text{striated}}}{\Delta M_{\text{control}}} = \frac{L J_{cw}}{2} \frac{12}{11} \frac{2}{w J_{cf}} \left( 1 - \frac{4 J_{cw}}{3 J_{cf}} \right) + \frac{12}{11} \frac{1}{N}. \quad (11)$$

This leads (using a magnetization ratio of  $\frac{1}{4}$ ) to

$$\eta^2 + \frac{3}{4} \eta - \frac{1}{61} \approx 0, \quad (12)$$

where  $\eta = J_{c2}/J_{c1}$ . Solving this equation leads to a  $J_{c2}$  that is 2% of  $J_{c1}$ . This is about two orders of magnitude off from the desired factor of 2000 noted earlier—but this should be achievable with appropriate modifications in the striping methods.

## VI. CONCLUSION

A simple investigation has been conducted, which indicates the potential of using weakly linked striations to allow current sharing between the HTS filaments of striated coated conductors, while still reducing the associated hysteretic loss. A discussion of the merits of this approach was included with the initial calculations indicating that for moderate to high-frequency applications, a superconducting link-enabled current-sharing scheme will have a better loss-sharing tradeoff than a normal-metal-based current sharing. The method proposed is capable of being performed on small samples as well as long lengths of ac conductors. An initial patterning of the superconducting tape's substrate or buffered substrate can be done by a variety of processes such as physical scribing, wet or dry etch, laser ablation, controlled deposition/growth on/of the basic (buffered) substrate, controlled removal from the basic (buffered) substrate, or even initial formation of the substrate. The important aspect, whether post- or preprocessing methods are used to the HTS deposition, is to create striated defects along the length of the HTS coated conductor such that the deposition or growth of the HTS layer will result in a multifilamentary structure that is separated by lower critical current-density “barriers” in the HTS films.

Indeed, it may be difficult in real systems to avoid this effect, because real striped coated conductor systems may have both the metallic and weak superconducting links present unintentionally along the lengths in any case. The mathematical descriptions given previously will be useful for those situations as well. However, we have demonstrated previously that it may be useful to intentionally induce the superconducting weak links if we wish to hedge against the possibility of filamentary degradation. We have also shown that such weak links can potentially be produced in real systems. If we control the strength of these weak links more closely (lowering the  $J_c$  from 2% of the base line  $J_c$  to 0.01%), it should be possible to have both the current sharing and low loss.



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